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# COMPARISONS OF $K_{Ic}$ MEASUREMENTS BY THE SHORT ROD AND ASTM E 399 METHODS

March 1979

Terra Tek, Inc.
Salt Lake City, Utah

AMMRC
Watertown, Massachusetts

Interim Report - Contract Number DAAG46-78-C-0040



Prepared for

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ABSTRACT

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## ABSTRACT

A multilaboratory blind comparison testing program was used to evaluate the accuracy of the short rod method of measuring the fracture toughness of metallic materials. Valid comparisons between $K_{Ic}$'s measured according to ASTM E 399 and by the short rod method were obtained for several steels, aluminum alloys, and titanium. The short rod $K_{Ic}$ values were consistently low, averaging 6 percent below the measurements according to E 399. A 4 percent adjustment in the short rod calibration constant, which had been previously evaluated only to ±7 percent, brings the two sets of $K_{Ic}$ measurements into very good agreement. The short rod method thus appears to be a viable alternative for measuring the fracture toughness of metallic materials.

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## INTRODUCTION

The value of fracture mechanics considerations in engineering design is now generally recognized. However, it has been stated that the basic ingredient of such considerations, the fracture toughness, is a material property which is difficult and expensive to measure.[1-5] The recently-proposed short rod method of measuring plane-strain fracture toughness[6,7] has appeared to offer a simpler, less-expensive alternative to the generally accepted ASTM E 399 method.[8] A comprehensive study of the short rod specimen geometry by finite element computer analysis and by experimental compliance measurements has been lacking, however, although a preliminary compliance calibration has been made.[9] A compliance study of closely related short bar specimens with chevron notches has also been recently completed.[10] Nevertheless, the short rod calibration has been based primarily on a few tests of 2014-T651 aluminum in which the short rod calibration constant was selected to produce the same $K_{Ic}$ as measured by E 399. A 7 percent uncertainty in that evaluation of the calibration constant was indicated.[6]

In addition to the calibration uncertainty, questions have been raised concerning the short rod's use of a steady-state crack rather than a fatigue pre-crack. Also, a recently-proposed elastic-plastic method of analyzing short rod data[11] promises to allow the use of much smaller specimens, but has not yet been conclusively tested.

Considering the several questions concerning the short rod method, notwithstanding the early promising results, it seemed that an appropriate way to further test the validity and accuracy of the technique would be to test its measurements of $K_{Ic}$ against ASTM E 399 $K_{Ic}$ measurements for a number of different metallic materials. Accordingly, a blind comparison testing program has been accomplished in which ASTM-valid $K_{Ic}$ measurements made by five different laboratories were compared with short rod $K_{Ic}$ measurements. This paper describes the test program and reports and discusses the test results.

## TEST PROGRAM DESCRIPTION

Six independent laboratories participated in the study by providing material in the form of broken halves of compact toughness (CT) specimens from which valid fracture toughness ($K_{Ic}$) data had already been determined in accordance with ASTM test standard E 399. The compact toughness halves were sent to Terra Tek, Inc., where they were machined into short rod specimens with the same crack orientation as the original CT specimens. Terra Tek then performed $K_{Ic}$ tests using the short rod technique, and forwarded the results to the Army Materials and Mechanics Research Center (AMMRC) which served as a repository for data collection. Only after completion of the short rod tests were Terra Tek personnel allowed to compare the results.

Table 1 lists the material, source code, material type, heat treatment if uncommon, original shape of plate thickness from when the CT specimen originated, and yield strength. As indicated in the table the materials examined were steel, titanium and aluminum. NASA-Lewis Laboratory was one of the six participants, but unfortunately their specimen was inadvertently destroyed; thus $K_{Ic}$ comparisons are presented for materials supplied by five independent laboratories.

The yield strengths of the successfully-tested steels ranged from a low of 503 MPa (75 ksi) for the Army designated HF-1 material developed for military applications to values in excess of 1380 MPa (200 ksi) for D6AC material used in aircraft components. Since the heat treatments for three of these steels are not common, they are also included in Table 1. Three additional steels were furnished by Westinghouse Research Laboratories, but these are not listed in Table 1 for reasons discussed in the Results and Discussion section.

The 6Al-4V (6-4) titanium material included in this study is a standard type which has yield strengths in excess of 860 MPa (125 ksi). The aluminum materials tested were of the standard alloys and heat treatments indicated in Table 1. Their yield strength values range from 393 MPa (57.0 ksi) to 456 MPa (66.1 ksi).

Table 1 — *Materials and Source.*

| MATERIALS | SOURCE CODE[a] | MATERIAL TYPE | HEAT TREATMENT | ORIG. SHAPE OR PLATE THICKNESS | YIELD @ 0.2% OFFSET MPa (ksi) |
|---|---|---|---|---|---|
| STEELS | 1 | HF-1 Isothermally Transformed | Austenitized at 1700°F, quenched to 1150°F, held at 1150°F for 1½ hours, then air cooled | 25 mm | 503 (73.0) |
| | 2 | ASTM A470 CrMoV Rotor Steel | Standard | 1.27 m dia., 6.73 m long | 626 (90.8) |
| | 3 | ASI 4340 | Quenched from 1475°F, tempered at 950°F 1 hour | 152x127x610 mm | 1070 (155) (estimated) |
| | 4 | D6AC | Austenitized, salt quench, double temper | Hollow rolled ring, 1.83 m dia., wall 76 mm thick | 1407 (204) |
| | 4 | D6AC | | | 1385 (201) |
| TITANIUM | 4 | 6-4 | Standard anneal | Irregular forging | 868 (126) |
| | 4 | 6-4 | Standard anneal | Irregular forging | 885 (128) |
| ALUMINUM | 3 | 2124 | T851 | 76 mm | 393 (57) |
| | 5 | 2124 | T851 | 140 mm | 406 (59) |
| | 5 | 7050 | T73651 | 83 mm | 456 (66) |
| | 5 | 7475 | T7351 | 44 mm | 450 (65) |

[a] Source Code

1. Army Materials and Mechanics Research Center (AMMRC)
2. Westinghouse Research Laboratories
3. George Washington University
4. Ladish Company
5. Alcoa Laboratories

# SHORT ROD TEST METHOD

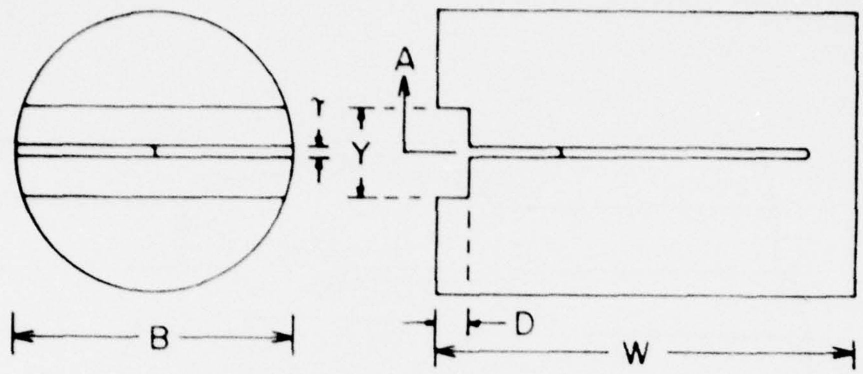
## Short Rod Test Configuration

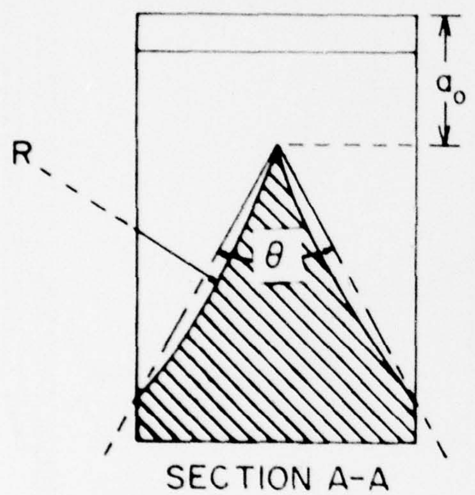
One could have chosen either the round short rod specimen configuration or the "squared off" version of the short rod, known as the short bar,[10,12] for the test series. However, most of the previous experience has been with short rod specimens, which are also somewhat easier to machine. Thus, short rods were used exclusively in these tests. The short rod specimen configuration is shown in Figure 1, where its dimensions are given in terms of its diameter, B.

The short rods were loaded by a special mechanism named a "Fracjack" (Figure 2) which was designed for convenience and accuracy in short rod and short bar testing. The grips on the Fracjack are slightly crowned, such that they contact the inside of the specimen grip grooves at a depth of 1.3 mm for th 25 mm diameter specimens of this study. The contact depth is very easily and accurately repeatable by simply placing the specimen on the Fracjack grips, where gravity holds it in place until the grips come in contact with the grip groove (Figure 2). The symmetry of the crowned grips about the lines of contact in the grip groove assures that the effective load line does not change, even in the event of a slight plastic deformation of the specimen grip groove by the hardened steel grips. Furthermore, the pivot axis of the Fracjack was selected such that the rotation of the grips during the test approximately matches the rotation of the specimen grip groove surfaces as the specimen mouth is forced open. This feature minimizes any change in the position of the load line that may otherwise occur by the crowned grips' contact point "walking" up the insides of the grip grooves as the specimen mouth is forced open. Friction between the grips and the specimen is also minimized by the strategically pivoted grips.

## The Nominal LEFM Short Rod Test

In this subsection we describe the idealized behavior of a short rod specimen which obeys the principles of linear elastic fracture mechanics (LEFM). The next subsection describes the variations from the ideal behavior which are commonly observed.




| SYMBOL | DEFINITION | VALUE |
|---|---|---|
| B | DIAMETER | B |
| W | LENGTH | 1.5B |
| $a_o$ | INITIAL CRACK LENGTH | .452B |
| $\theta$ | SLOT CHORD ANGLE | 59.0° |
| $\Upsilon$ | SLOT THICKNESS | .015B |
| R | RADIUS OF SLOT CUT | 2.5B |
| D | GRIP GROOVE DEPTH | .120B |
| Y | GRIP GROOVE WIDTH | .313B |

Figure 1. Short rod specimen configuration and dimensions.

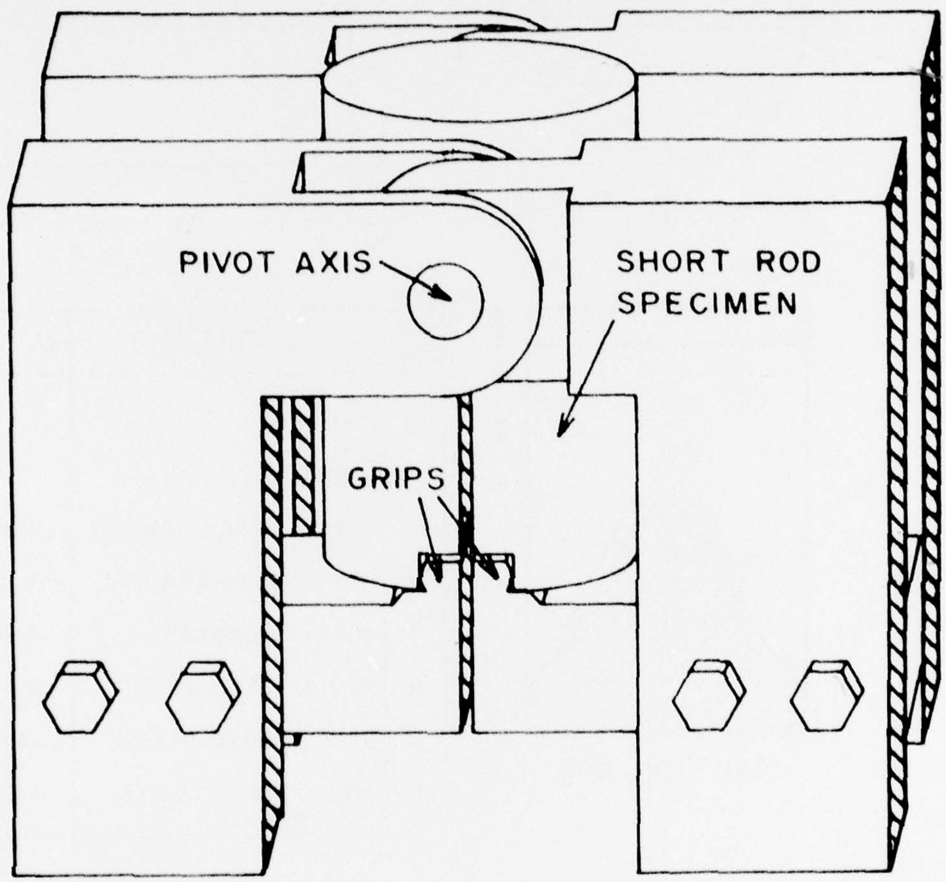



Figure 2. Schematic of the Fracjack mechanism for testing short rod specimens.

The short rod test is conducted by slowly increasing the spacing between the grips, thus forcing the mouth of the specimen open under controlled displacement (stiff machine) conditions. A clip gage is attached to the outside of the specimen approximately at the load line to measure the mouth opening displacement. A load-displacement plot is made, yielding a record similar to that shown in Figure 3(a). At point A, where the initial elastic loading first deviates from linearity, the crack is initiating at the point of the ligament in the specimen (shaded area in Figure 1). However, the specimen design makes the crack growth initially quite stable, and an ever-increasing load is required to advance the crack until it reaches a critical length, $a_c$, where the load goes through a smooth maximum. Thereafter, the crack-advancing load decreases with further crack growth, but the crack growth can still be stable with controlled-displacement loading. Two or more relaxation and reloading paths may be drawn when the load is near the maximum value to give an indication of the degree to which LEFM conditions may be violated. For ideally LEFM tests, the unloading slopes should point to the origin of the load-dispacement path.

Because the crack length, $a_c$, at the time of the peak load, $P_c$, is a property of the specimen geometry and is independent of the specimen material for LEFM tests, the peak load is used in the calculation of $K_{Ic}$. The equation for $K_{Ic}$ is[6]

$$K_{Ic} = AP_cB^{-3/2}, \tag{1}$$

where A is the short rod calibration constant and B is the specimen diameter. The value of A which was used for this study was 21.2, which was the best estimate based on the calibration in reference 6 and the current test configuration.

## Variations from Ideal Behavior

Although some materials have been tested which show essentially the ideal behavior of Figure 3(a), most tests contain varying degrees of one or more of the following nonideal characteristics.

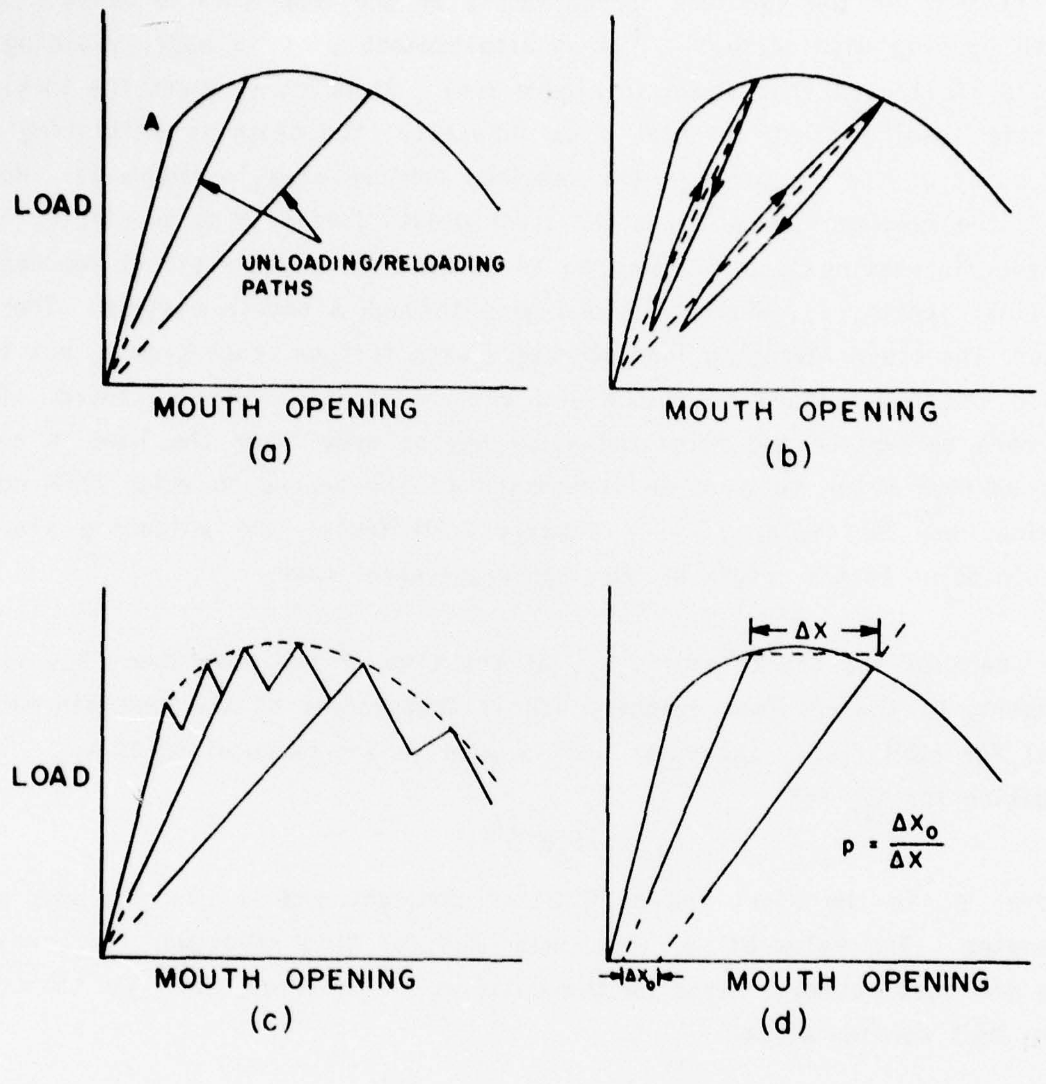



Figure 3. Types of load vs. mouth opening curves observed. (a) Ideal LEFM curve. (b) Hysteresis in unloading/reloading paths. (c) Crack jumps. (d) Elastic-plastic specimen response

Unloading/Reloading Hysteresis (Figure 3(b)): This effect is common, and is of concern because it makes the unloading slope ambiguous, and thereby causes an uncertainty in the measure of the specimen plasticity[11], i.e., the degree to which LEFM assumptions may be violated. The hysteresis may be caused by the presence of "bridges" of material which still connect the two crack surfaces well behind the actual crack front. The existence of such bridges is to be expected from observations of crack nucleations ahead of the crack tip. The last of the material to be severed by the joining nucleations may constitute the bridges of interest here. Also, if more than one unloading/reloading cycle is done at a given crack length, the hysteresis decreases with each successive cycle, as would be expected due to the plastic working and breaking of some of the bridges.

The bridges account for the observed hysteresis as follows. During the initial part of the unloading, the residual bridges react elastically, making the specimen behave as though the crack length were shorter than it really is. This causes the initial relaxation path to be rather steep. With further relaxation and closure of the mouth of the specimen, however, the residual bridges yield in compression and contribute a more nearly constant resistance to the closing of the specimen mouth. When the resistance to closing is constant, the unloading slope signifies the actual crack length, although the unloading path is offset by the constant resistance to unloading. Later, when the unloading is nearly complete, a terminal steepening of the unloading path may occur due to the crack closure effect. On reloading, the resistance offered by the bridges is in the opposite direction since they must now be plastically stretched rather than compressed. Hence, we have the observed hysteresis.

Since both the initial and final slopes on the unloading path may be steepened as described above, it is the central minimum slope which gives the best indication of the crack length through the compliance correlation. Therefore, one can construct a good approximation to the idealized elastic unloading path by drawing a line through the initial unloading point, and by choosing the slope of the line to be equal to the minimum slope on the

actual unloading path. Artificial unloading paths drawn according to this rule were used to evaluate the plasticity of specimens which produces a hysteresis in the unloading/reloading paths.

The hysteresis was largest for the A470 and the HF-1 steel specimens. It was small to almost nil for the other materials of this study.

Crack Jumps (Figure 3(c)): This behavior is characterized by nearly linear loading until the crack suddenly jumps forward with an audible "pop". The fast-moving crack arrests at a lower load level after propagating a short distance. When the load is again increased, little further crack growth takes place until the next sudden jump, etc. Each time the crack begins a forward jump, it can be assumed that the stress intensity factor is $K_{Ic}$. Thus, a smooth curve drawn through the points at which the jumps started will have maximum, $P_c$, from which $K_{Ic}$ can be calculated by equation (1). Similarly, one can obtain the value of the stress intensity factor which allows the fast-moving crack to arrest, $K_{Ia}$, by drawing a smooth curve through the points at which the crack arrested. In this study, the A470 and the HF-1 steels displayed the crack jump behavior.

Elastic-Plastic Specimen Response (Figure 3(d)): If the specimen behaves purely elastically, the unloading path should lead to the origin of the load vs. mouth opening curve, since the specimen mouth should close completely at zero load in the absence of any plasticity. However, the material within the plastic zone at the crack tip tends to prop the specimen mouth open such that it does not close completely unless the specimen is very large compared to the plastic zone size. Thus, the measure of the residual specimen mouth opening after relaxation zero load can be taken as an indication of the degree to which LEFM assumptions are violated.

A recent paper[11] has treated elastic-plastic specimen behavior in detail, and a method was derived for recovering the LEFM $K_{Ic}$ value from such specimens, provided the crack-tip plastic zone is still relatively small compared to the specimen size. The method defines the specimen plasticity,

p, as the increase in residual mouth opening between two relaxations divided by the increase in mouth opening at the average crack-advancing load between the two relaxations (Figure 3(d)):

$$p = \frac{\Delta x_o}{\Delta x} \quad . \tag{2}$$

It is then shown that $K_{Ic}$ for such a short rod specimen is given by[11]

$$K_{Ic} = \frac{AP_c}{B^{3/2}} \left(\frac{1+p}{1-p}\right)^{1/2} \quad . \tag{3}$$

Notice that equation (3) reduces to equation (1) when the plasticity is zero.

The measured plasticities of the short rod specimens of this study ranged from zero to almost unity. The larger plasticities precluded meaningful short rod $K_{Ic}$ results.

## RESULTS AND DISCUSSION

Three steels which were provided by Westinghouse for the $K_{Ic}$ comparison testing program do not appear in Table 1 because the attempts to test them with the 25 mm diameter short rod specimens used in this study were unsuccessful. The steels were ASTM A471 NiCrMoV rotor steel, AISI 403 modified 12 Cr stainless rotor steel, and ASTM A217 2-1/4 CR-1 Mo cast steel. The approximate values of $B_{min} = 2.5(K_{Ic}/\sigma_{ys})^2$ for these steels were 50 mm, 150 mm, and 570 mm, respectively.[13] Based on earlier experience[11] it had been anticipated that the 25 mm diameter short rod specimens should be capable of testing materials with $B_{min}$ values up to about 70 mm. Thus, it is not surprising that the two steels with $B_{min}$'s of 150 and 570 mm could not be tested because of very large plasticities. The A471 steel with a $B_{min}$ of about 50 mm displayed a very large crack jump behavior (Figure 3(c)), which, when combined with the somewhat marginal $B_{min}$ value, precluded a successful $K_{Ic}$ test.

Table 2 shows the test results for those materials which were successfully tested by the 25 mm diameter or smaller short rod specimens. In Table 2 and the rest of this paper, $K'_{Ic}$ refers to fracture toughness measurements made by the short rod method, while $K_{Ic}$ refers to measurements made according to E 399. Notes c, e, and f of Table 2 which express reservations about some of the data were contained also in the letter[14] which originally reported the short rod results to AMMRC; hence, these notes have not been added with the benefit of hindsight. In particular, with reference to Note f, the following quotation from the reporting letter is of interest.*

> "I have saved the actual CT crack surfaces of the three Alcoa materials by sawing them off intact before having the rest of the material machined into short rods. On the No. 3 material it can be seen that the fatigue pre-crack had a rather unusual shape, inasmuch as the center-thickness part of the pre-crack was slightly retarded with respect to the rest of the crack front, whereas the more usual fatigue pre-crack takes on a slight "thumb-nail" shape in which the center-thickness region tends to lead the rest of the pre-crack (see Figure [4]). The retardation of the center-thickness region of the pre-crack might be interpreted as an indication of an increase in toughness toward the center of the original plate from which the CT specimen was made. This hypothesis seems to be supported by the somewhat rougher fracture surface texture near the center of the specimen, both on fatigue crack surface and on the running crack surface.... The point of this discussion is that the 1-inch diameter short rod specimens were cut from the center thickness of the supplied 1-3/4 inch thick CT specimen. Moreover, the width of the crack front between the slots in the short rod specimen is only about 0.33 inch at the time of the $K'_{Ic}$ measurement. Thus, the short rod results reported for specimens A3-2 and A3-3 represent the toughness almost precisely at the mid-thickness plane of the CT specimen, where the material appears to have been substantially tougher than closer to the lateral surfaces. The CT

* The No. 3 material and specimens A3-2 and A3-3 of the quotation were made of the 7475-T7351 aluminum to which Note f applies.

TABLE 2 — $K_{Ic}$ *Comparisons.*

| MATERIAL(a) | CRACK ORIEN-TATION | $B_{min} = 2.5(K_{Ic}/\sigma_{ys})^2$ mm (in) | CT SPECIMEN THICKNESS mm (in) | SHORT ROD DIAMETER mm (in) | $K_{Ic}$ PER ASTM E 399 $MPa\sqrt{m}$ ($ksi\sqrt{in}$) | $K'_{Ic}$ PER SHORT ROD $MPa\sqrt{m}$ ($ksi\sqrt{in}$) | % DIFF. $\frac{100}{K_{Ic}}(K'_{Ic}-K_{Ic})$ | COMMENTS |
|---|---|---|---|---|---|---|---|---|
| **STEELS:** | | | | | | | | |
| HF-1 | T-L | 8.9 (.35) | 22.2 (.88) | 22.2 (.88) | 30.1 (27.4) | 28.8 (26.2) | - 4.4 | |
| | | | | 22.2 (.88) | | 27.4 (24.9) | | Notes b,c |
| ASTM A470 | C-R | 15.8 (.62) | 25.4 (1.00) | 25.4 (1.00) | 49.9[d] (45.4) | 47.8 (43.5 | - 4.2 | |
| | | | | 25.4 (1.00) | | 51.1 (46.5) | | Notes b,e |
| ASI 4340 | L-T | 13.0 (.51) | 32.0 (1.26) | 25.4 (1.00) | 77.0 (70.0) | 81.4 (74.0) | 5.7 | |
| D6AC | L-C | 17.5 (.69) | 31.8 (1.25) | 25.4 (1.00) | 118.2 (107.5) | 111.1 (101.0) | - 6.0 | |
| D6AC | L-C | 19.3 (.76) | 31.8 (1.25) | 25.4 (1.00) | 122.2 (111.1) | 114.3 (103.9) | - 6.5 | |
| **TITANIUM:** | | | | | | | | |
| 6-4 | T-L | 23.9 (.94) | 31.8 (1.25) | 25.4 (1.00) | 85.1 (77.4) | 69.5 (63.2) | -18.3 | |
| 6-4 | T-L | 15.2 (.60) | 31.8 (1.25) | 25.4 (1.00) | 69.1 (62.8) | 66.8 (60.7) | - 3.3 | |
| **ALUMINUM:** | | | | | | | | |
| 2124-T851 | T-L | 11.9 (.47) | 31.8 (1.25) | 25.4 (1.00) | 27.2 (24.7) | 24.9 (22.6) | - 8.5 | |
| 2124-T851 | L-T | 20.1 (.79) | 38.1 (1.50) | 25.4 (1.00) | 36.4 (33.1) | 34.6 (31.5) | - 4.8 | |
| 7050-T73651 | T-L | 13.5 (.53) | 50.8 (2.00) | 25.4 (1.00) | 33.5 (30.5) | 31.5 (28.6) | - 6.2 | |
| | | | | 25.4 (1.00) | | 30.2 (27.5) | - 9.8 | Note b |
| 7475-T7351 | L-T | 37.6 (1.48) | 44.5 (1.75) | 25.4 (1.00) | 55.2 (50.2) | 62.6 (56.9) | | Note f |
| | | | | 25.4 (1.00) | | 64.0 (58.2) | | Notes b,f |

**NOTES:**

(a) Materials are listed in the same order as in Table 1.
(b) Duplicate short rod specimens were prepared from the supplied CT specimen.
(c) Estimated 10% uncertainty in $K'_{Ic}$ due to out-of-tolerance short rod specimen and large pop-in; thus, the $K_{Ic}$ comparison is less significant than for the other HF-1 short rod specimen.
(d) Average of 3 tests.
(e) Estimated 10% uncertainty in $K'_{Ic}$ due to large crack jumps; thus, the $K_{Ic}$ comparison is less significant than for the other A470 short rod specimen.
(f) Comparison of $K'_{Ic}$ with $K_{Ic}$ is invalid because toughness varied with position in the material. See discussion in text.

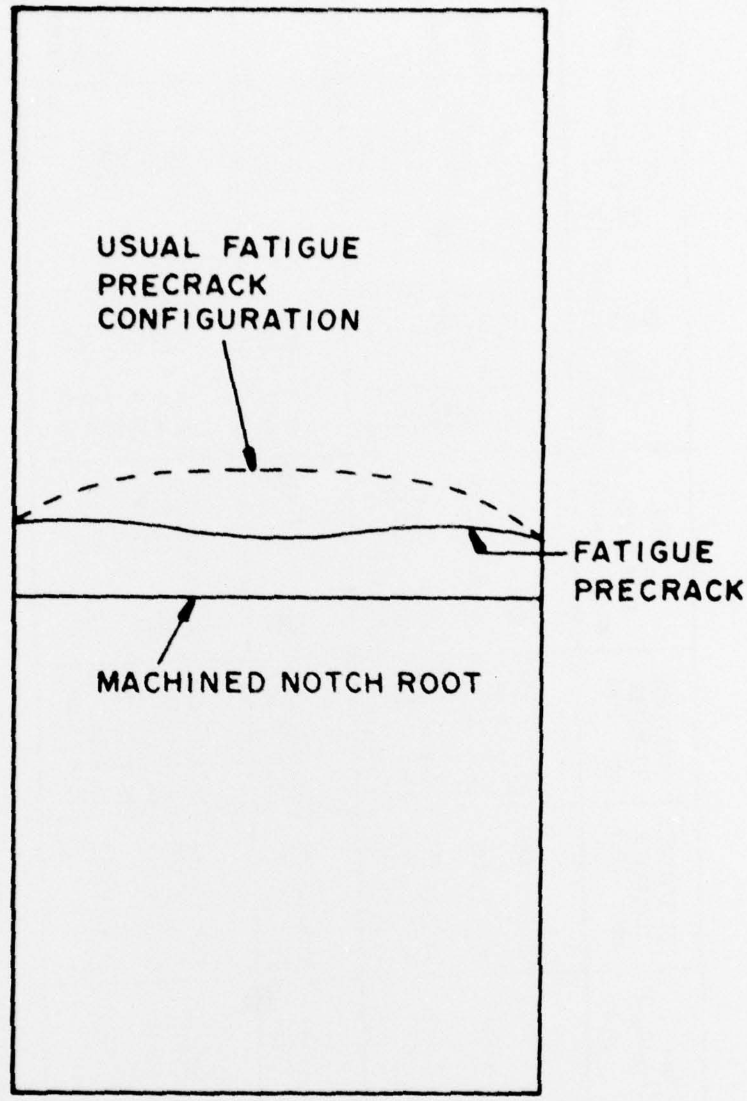



Figure 4. Fatigue pre-crack configuration on the CT specimen half which supplied the 7475-T7351 material from Alcoa.

specimen $K_{Ic}$ result, on the other hand, should be more representative of the average toughness over the 1-3/4 inch thickness of the specimen, which may include less-tough material more distant from the central region. Thus, I would expect that the short rod toughness measurement on the Alcoa #3 material may be somewhat higher than the toughness reported by Alcoa."

The letter goes on to state that previous short rod measurements have shown $K'_{Ic}$ variations of as much as 25 percent between the 1/4-thickness point and the mid-thickness point in a 75 mm thick plate of aluminum, which incidentally, was also 7475-T7351. Thus, although the short rod measurements of the 7475-T7351 aluminum of this study are considered meaningful, no valid comparison with the ASTM $K_{Ic}$ measurement can be made, other than that $K'_{Ic}$ is larger than $K_{Ic}$, as predicted.

It would seem that the ability of the short rod to measure the local toughness in a material should prove to be quite useful, especially considering that such measurements according to E 399 can be precluded by the $B_{min}$ requirement.

Although the short rod data reported in Table 2 were obtained using the elastic-plastic data analysis method,[11] the present results do not constitute a conclusive test of the utility of the elastic-plastic theory. The reason is that the specimen plasticities were all small in those specimens for which valid $K_{Ic}$ comparisons were obtained, such that the elastic-plastic treatment of the data affected $K'_{Ic}$ by only 0 to 4 percent, except for the 2124-T851 L-T test, where the effect was about 7 percent. The application of the elastic-plastic data analysis generally decreased the percent difference between $K_{Ic}$ and $K'_{Ic}$, and for the most part produced a tighter grouping of the percent differences.

The percent differences listed in Table 2 indicate that the short rod $K'_{Ic}$ measurements averaged 6.0 percent lower than the E 399 $K_{Ic}$ values. Nine of the eleven $K'_{Ic}$ measurements were within ± 4 percent of the average 6

percent low figure. Recall that one of the objectives of the present test series was to check the short rod calibration constant, considering the original 7 percent uncertainty attached to its evaluation,[6] and considering that the test configuration has changed somewhat since that time. Therefore, in view of the rather tight grouping of most of the $K'_{Ic}$ values at around 6 percent below the corresponding $K_{Ic}$ values, it would seem that an upward adjustment of the short rod calibration constant, A, of at least 4 percent is justified. Such an increase would also be consistent with a recent preliminary compliance calibration of the short rod specimen.[9] If the $K'_{Ic}$ values are recalculated with the 4 percent increase in A, i.e., using

$$A = 22.0 \tag{4}$$

in equation 3, each percent difference listed in Table 2 is increased algebraically by approximately 4 percent. The $K'_{Ic}$ values then average only 2 percent less than the $K_{Ic}$'s, and the average magnitude of the percent difference is only 4 percent. It seems quite possible that interlaboratory $K_{Ic}$ tests using only the E 399 method may show a similar scatter of results. Therefore, the present comparison test series suggests that the short rod method can be used for toughness measurements of a wide range of metallic materials, and that the $K'_{Ic}$ results should be essentially the same as those obtained by the E 399 method. Perhaps the next step in providing the needed background for the short rod method should be an accurate three-dimensional finite element study to evaluate the stress state and stress intensity factor in the vicinity of the crack tip.

## SUMMARY AND CONCLUSIONS

The validity and accuracy of the short rod method of measuring plane-strain fracture toughness was tested by comparing short rod $K'_{Ic}$ measurements with $K_{Ic}$ measurements made according to ASTM method E 399. Comparisons were made for several steels and aluminum alloys, and for titanium, using a blind testing procedure to eliminate bias. The short rod measurements averaged 6 percent lower than the E 399 $K_{Ic}$ measurements, indicating that the short rod calibration constant, previously evaluated to ±7 percent, should be increased. By increasing the constant by 4 percent, the short rod results

averaged only 2 percent below the E 399 $K_{Ic}$ values, and the average magnitude of the percent difference in $K_{Ic}$'s is only 4 percent for this study.

It is therefore concluded that the short rod calibration constant, A, for the test configuration used in this study should be increased from its previously estimated value by 4 percent to A = 22.0. The comparison tests of this study indicate that the short rod test method will produce essentially the same toughness values as would be measured by ASTM method E 399 for many metallic materials. However, when the toughness varies with position in the bulk material, the short rod method has the capability of measuring much more localized toughness values than the E 399 method.

A three-dimensional stress analysis of the short rod specimen configuration is recommended to provide accurate analytical information on the state of stress and the stress intensity factor at the crack tip.

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| 1 | Prof. D. Drucker, Dean of School of Engineering, University of Illinois, Champaign, Illinois 61820 |
| | University of Illinois, Urbana, Illinois 61801 |
| 1 | ATTN: Prof. H. T. Corten, Department of Theoretical and Applied Mechanics, 212 Talbot Laboratory |
| 1 | Prof. T. J. Dolan, Department of Theoretical and Applied Mechanics |
| 1 | Prof. J. Morrow, 321 Talbot Laboratory |
| 1 | Mr. G. M. Sinclair, Department of Theoretical and Applied Mechanics |
| 1 | Prof. R. I. Stephens, Materials Engineering Division, University of Iowa, Iowa City, Iowa 52242 |
| 1 | Prof. R. I. Stephens, Materials Engineering Division, University of Iowa, Iowa City, Iowa 52242 |
| 1 | Prof. D. K. Felbeck, Department of Mechanical Engineering, University of Michigan, 2046 East Engineering, Ann Arbor, Michigan 48109 |
| 1 | Dr. M. L. Williams, Dean of Engineering, 240 Benedum Hall, University of Pittsburgh, Pittsburgh, Pennsylvania 15260 |
| 1 | Prof. A. Kobayashi, Department of Mechanical Engineering, FU-10, University of Washington, Seattle, Washington 98195 |
| | State University of New York at Stony Brook, Stony Brook, New York 11790 |
| 1 | ATTN: Prof. Fu-Pen Chiang, Department of Mechanics |
| 1 | Dr. Robert S. Shane, Shane Associates, Inc., 7821 Carrleigh Parkway, Springfield, Virginia 22152 |
| | Director, Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172 |
| 2 | ATTN: DRXMR-PL |
| 2 | DRXMR-PR |
| 1 | DRXMR-PD |
| 1 | DRXMR-AP |
| 1 | Author |